EFFECT OF STIFFENERS ON STRUCTURAL BEHAVIOR OF STEEL LIQUIDS TANK

Mahmood Hunar DHEYAALDIN
Research scholar, Department Civil Engineering
Mahmood.honer@gmail.com

Mustafa ÖZAKÇA
Professor, Department Civil Engineering
ozakca@gantep.edu.tr

Abubaker Sami DHEYAB
Research scholar, Department Civil Engineering
bakersami.bd@gmail.com

ABSTRACT: The finite element (FE) method is used to conduct an analysis of liquid storage tanks This research has focused on the behaviors, under static condition, free vibration and buckling of steel liquid tanks which are designed according to API 650 standards. The mechanical characteristics of the materials and the real geometrical and load measures have been considered in the numerical model. These storage tanks are connecting with American standard steel shape profiles. The equivalent stress (Von-Mises) distribution, deformation in the circular wall of the liquid tank, buckling load and fundamental frequency are computed using finite element method in order to investigate the effect of type of the stiffener, number of course and location of stiffener on the structural behavior of liquid tanks. The uses of the stiffener decrease the stress of wall tank and improve the other structural behaviors.

Key words: Finite element method, Stiffener, Storage tank, API-650 standard

INTRODUCTION

The design and maintenance of atmospheric and low-pressure vessels for liquid storage is becoming ever more vital as water and crude oil storage capacity utilization rises and water and oil storage capacity demands grow globally. On the other hand, failure of liquid storage tanks may lead to disaster due to the water crisis, fire, health and environmental hazard owing to the spread of chemicals or/and liquid fuel. Cylindrical tanks have been used in almost all sectors of industry, mainly as the tanks for storage of water or other liquids. Ground tanks, which are also known as reservoirs, can take different shapes (e.g. rectangular, cylindrical, and cylindrical with conical base). From the structural point of view, cylindrical tanks are very suitable as the external walls in the horizontal direction have been loaded only by tension or pressure, while in other types of tanks, the load is combined. Cylindrical tanks are appropriate also with respect to the low consumption of material needed for their construction. Presently more than 70 % of all tanks are of the circular ground plan. In a cylindrical liquid storage tank, it is further classified, including the open top tank, fixed roof tank, external floating roof and internal floating roof tank. The type of storage tank used for the specified product is principally determined by safety and environmental requirements. Operation cost and cost-effectiveness are the main factors in selecting the type of storage tank (Chauhan, 2012).

There are two approaches for modeling liquid storage tanks by using analytical and numerical modeling techniques. The analytical modeling technique has been defined as a simplified model that had been developed by different researchers (Elkholy et al 2014) However, the analytical models including the fluid-structure interaction system and/or the soil structures integration system are very complex to solve. The most powerful numerical method is finite element (FE) method. In a method, the main objective is to create a mathematical representation of the engineering system that reflects its actual geometry and behavior (Housner et al 1963). The FE structural analysis program, ANSYS (Canonsburg, 2013b) was used in this study to produce the FE modeling needed for the tank analysis. Building FE models in ANSYS requires familiarity with the ANSYS operating manual and element library. Each element in ANSYS has specific properties and behaviors to be defined according to the structure in the problem (Elkholy et al, 2014) (Canonsburg, 2013a).

Because of the complexity added by the grid of rafters and rings, researchers and designers working on advanced analysis models to simulate the effect of such as fluid-structure interaction, soil structure interaction, buckling behavior, seismic load, wind load etc. (Burgos et al, 2015) Meanwhile, some of the researchers attempt to simplify the structural analysis by eliminating the three-dimensional grid and substituting it by a modification in the thickness of the roof. Such "equivalent" roof is a self-supported shell with a modified thickness, but also the weight needs to be adjusted in order to avoid having an excessively heavy roof which would buckle under self-weight. This approach may be found in many research papers (Fakhım et al 2009). Even simpler models have been considered in the literature, in which the roof is completely eliminated and its influence is represented by simply supported boundary conditions at the top of the cylindrical shell (Cao et al, 2010) Such simplifications are not motivated by computer time constraints but are frequently made to simplify modeling and data entry.

There are many numbers of options available for liquid tanks. Back in 1961, the American Petroleum Institute published the API Standard (API, 2013) which covers material, design, fabrication, erection, and inspection of petroleum tanks. The standard is designed to provide flexibility for the owner: As long as bulk oil storage tanks meet these minimum requirements, they can be of any size. Safety is a priority, but beyond that, a tank buyer has a lot of options.

The main objective of the present work is to investigate number of course, the number, location and type of stiffener on structural performance of liquids tanks. The cylindrical tanks are initially design based on API 650 code (API, 2013) In this preliminary design, wall thicknesses, number of courses and stiffener are evaluated. The FE structural analysis program, ANSYS (Canonsburg, 2013b) was used in this study to investigated the structural behavior of preliminary designed liquid shells in details. The critical buckling load, fundamental frequency, deformations and stress distribution in cylindrical liquid tank are computed.

Liquid Storage Tank Design

A tank design must first be completed using static analysis before evaluating and designing a tank for seismic loads and buckling. Many different tank configurations were chosen in order to encompass a wide range of results. These configurations were characterized by their ratio of height to the radius, commonly referred to as the aspect ratio. Low and high aspect ratios correspond to broad and slender tanks, respectively. Broad and slender tanks behave in different manners and, therefore, should be expected to have different limiting design criteria. For example, a tank with a large radius contains more liquid per foot of elevation than small radius tank, and therefore, would be expected to produce higher total inertial forces on the shell wall compared to a tank with identical height and smaller radius. In this sense, impulsive mass contributions increase with an increase in tank radius while maintaining a constant depth of liquid. Broad tanks, in general, generate larger free surface waves and therefore have higher convective mass proportions compared to tall, slender tanks. For high aspect, ratios stability can control the design, where overturning and uplift of unanchored tanks are of great concern, while material limits are still critical (Spritzer et al, 2017).

Tank design codes reflect the culmination of decades of work by many dedicated individuals. Using these standards helps to ensure that tanks will be able to stand the rigors of the elements and conditions to which they are subjected. They ultimately lie in the pages of the following codes and standards (Mayeux et al, 2016):

- American Petroleum Institute (API) 650 (API, 2013)
- BS EN 14015:2004 (British Standards Institution (BSI), 2004)
- API 620 (American Petroleum Institute, 2002)

Liquid storage tank design based on API 650

Tank thickness: The API 650 code can be used for designs of welded liquid storage steel tanks where the internal pressure is less than or equal to 2.5 psi. The calculation of the thickness of the liquid cylindrical storage tank is explained in Section 3.6 of API 650 (API, 2013) In this section, there are two methods for consideration:

- Calculation of Thickness by the 1-Foot Method
- Calculation of Thickness by the Variable Point Method.

The 1-foot method computes the required plate thickness at a distance of one foot above the bottom of each shell course and is applicable to tanks 200ft (61 m) and less in diameter. The basic equation in SI customary units looks something like this:

$$\text{thickness required} = \frac{4.9D(H-0.3)G}{(S_d)(E)} + CA$$

The variable point method is an alternative to the 1-foot method and can be used for tanks in excess of 200ft (61 m) in diameter. The variable point equation in SI units is as follow

$$\text{Thickness required} = \left(1.06 - \frac{0.0696D}{H}\sqrt{\frac{H \times G}{S}}\right)\left(\frac{4.9H \times D \times G}{S}\right) + CA$$

Where: H is the design fluid height in m. D is the nominal tank diameter in m. G is the specific gravity of the contents. S is the tank wall material allowable tensile stress for the operating or test condition. CA is the corrosion allowance, if any API 650 storage tanks are often designed to work at temperatures of up to 500ºF (260ºC). For these higher temperature designs, the allowable stress of the material decreases. As a result, the required wall thickness increases in a linear fashion when using the 1-foot method and in a slightly non-linear fashion when using the variable point method. In addition to causing hoop stress and longitudinal stress in the tank wall, the slight internal pressure causes a tensile force (pressure × area) to be produced. This force pulls upward on the tank wall. This positive upward force is countered by the weight of the tank and roof (if not column-supported). If the net force is upward in any case or condition, the tank must be held down by anchor bolts. The basic internal pressure case is just one example. There are several other uplift formulas in Tables 5.21a (metric) and 5.21b (imperial), which must also be considered. The net uplift due to design pressure formula from Table 5.21b Addendum 2in API 650 (API, 2013).

Stiffeners: By definition, ring stiffeners are local stiffening members that pass around the circumference of the shell of revolution at a given point on the meridian. Normally they are attached to the interior of the shell of the tank and are formed as single plated sections WT, C or L profiles. The rings are assumed to have limited stiffness for deformations out of their own plane (meridional displacements of the shell) but they should be stiff for deformations in the plane of the ring.(Baniotopoulos et al 2008). According the API 650 (API, 2013); the maximum spacing of intermediate stiffeners

$$H_{safe} = \frac{(ts_{min})^{2.5}(E)}{45{,}609D^{1.5}(P_S)}$$

the number of intermediate stiffeners required, Ns, based on, $H_{safe.}$

$$Ns + 1 = H_{TS} / H_{safe}$$

and the spacing of intermediate stiffeners on the transformed shell height in accordance with the following equation:

$$\text{Spacing} = H_{TS} / (N_S + 1)$$

Where ts_{min} is minimum thickness of thinnest shell course, mm, E is modulus of elasticity of the plate material MPa, D is nominal tank diameter, m, P_S is total design external pressure for design of shell, kPa (lb/ft^2).Ps = the greater of 1) the specified design external pressure, P_e, excluding wind or 2) $w + 0.4P_e$

Analysis and design of liquid storage tank using ANSYS.

The development of this research was carried out by the construction of numerical modeling of the tank with help of the computer program ANSYS 17.2. The three-dimensional FE model of self-supporting dome tank was modeled as surfaces using the pre-processor section in ANSYS. The selection of a suitable element for a given application is not a trivial matter and will directly influence the computational time and accuracy of the results. FE models developed for this study consider the tank wall and base system to be represented and modeled by solid shell element.

DESIGN EXAMPLE --- SELF-SUPPORTING DOME TANK

Geometry, loading and material properties

The specific tank considered in this section is shown in Figure 1 with inner diameter D = 20 m and high of the tank (liquid level) H = 12 m. The design input data is listed in Table 1. The tank is designed for five different courses (2, 3, 4, 5 and 6 courses) and the results are compared for best solution. The courses have equal high. The tank is subjected to hydrostatic loading of a liquid of weight per unit volume and external pressure on the shell wall. The tank is only supported from bottom plate which is fixed support.

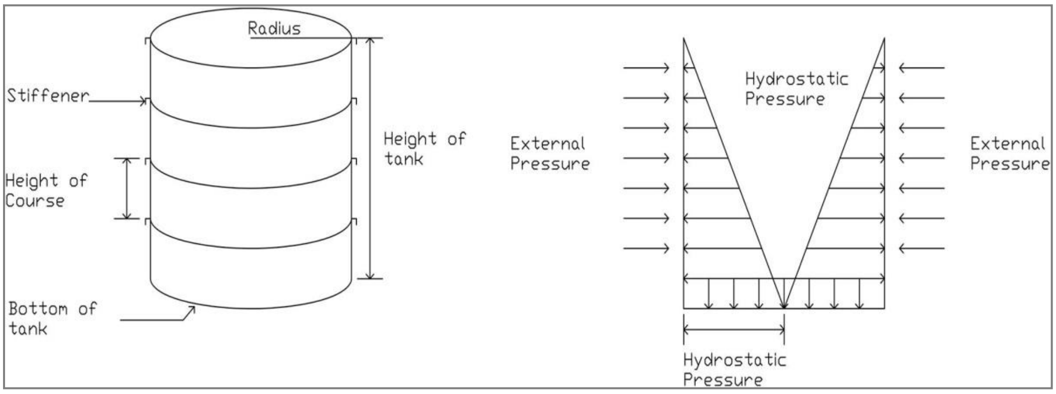

Figure 1 Geometry and loading of tank

Table 1 Design input data

Shell Data	
Roof type	Self-supporting dome
Density of contents	988.2 kg/m^3
External pressure	3 kPa
Hydrostatic load	ρgh =0.11633
Max. Design Temperature	60 C^o
High liquid level	12 m
Basic Wind Speed	190 km/h
Live load	1.5 kN/m^2

Material Data	
Material	A36 M Grade
Material Group	Group 1
Min. Yield Strength	250 MPa
Min. Tensile Strength	400 MPa
Modulus of Elasticity	200000 MPa
Density	7850 kg m^3
Passion's	0.3

Design of tank based on API 650 standard.

The 1-foot method is used to compute the thickness of each courses. Each courses are equal height. Lap welded bottom plates is used and thickness is computed according to API 650 Section 5.4. There is a wind girder at the top in order to restraint displacements in the upper part of the tank. This is one of the typical stiffening ring sections for tank shells illustrated in API 650 (see details in Figure 5.24 of API 650 (API, 2013)). The number, locations and dimensions of intermediate stiffeners and dimensions of the top wind girder are computed according to API 650 Section 5.9 (API, 2013). The details of the designed tank (according to API 650) are given in Table 2. The thickness of the bottom plate for all courses cases is 9 mm

FE analysis of the liquid storage tank

The FE package ANSYS is employed to carry out the analyses. The 8-node, connectivity, first-order interpolation, stress/displacement continuum solid shell 190 element with reduced integration is chosen to discretize the cylindrical wall. This element has three degrees of freedom at each node: translations in the nodal x, y, and z directions Thus, connecting SOLSH190 with other continuum elements requires no extra efforts. A degenerate prism option is available, but should only be used as filler elements in mesh generation. The element has plasticity, hyper elasticity, stress stiffening, creep, large deflection, and large strain capabilities. It also has mixed u-P formulation capability for simulating deformations of nearly incompressible elastoplastic materials, and fully incompressible hyper elastic materials. The element formulation is based on logarithmic strain and true stress measures. And CONTA174 is used to represent contact and sliding between 3-D "target" surfaces (TARGE170) and a deformable surface, defined by this element. The element has the same geometric characteristics as the solid or shell element face with which it is connected. The element is defined by eight nodes (the underlying solid or shell element has midside nodes). It can degenerate to a six-node element depending on the shape of the underlying solid or shell elements (Canonsburg, 2013).

Table 2. The summary of tank design according to API 650

Number of Course	Thickness of courses (mm)	Number of intermediate Stiffener	Inertia of stiffener (constant stiffener) (cm^4)	Inertia of stiffeners (cm^4)	Location of stiffener from the top (mm)
2	11	1	$I_{1,top}$=224	I_{top}= 220.14	12000
	11			I_1=468.84	6390
3	10	1	$I_{1,top}$=176	I_{top}= 173.36	12000
	10				
	11			I_1= 468.84	5030
4	9	2	$I_{1,2,top}$=176	I_{top}= 173.36	12000
	9				
	9			I_1= 223.56	3870
	11			I_2= 223.56	
5	8	3	$I_{1,2,3,top}$=142	I_{top}= 140.09	12000
	8				
	8			I_1= 134.58	2880
	9			I_2= 134.58	5760

	11			I_3= 180.66	9130
6	7	4	$I_{1,2,3,4,top}$=97.20	I_{top}= 140.09	12000
	7				
	7			I_1= 96.38	2060
	8			I_2= 96.38	4210
	9			I_3= 134.58	6250
	11			I_4= 298.35	10120

For stiffener, three type of profiles (see Figure 2) which have section details satisfying the inertia requirement stated in Table 2 are investigated. The tank is analyzed for following cases:

Case 1: without stiffener

Case 2: constant stiffener (unequal L angle with right orientation)

Case 3: variable stiffener (unequal L angle with right orientation)

Case 4: variable stiffener (unequal L angle with left orientation)

Case 5: variable stiffener (C section)

Case 6: variable stiffener (WT-section)

Case 1 which is tank without stiffener is considered in order to investigate the effect of stiffener. Case 1 does not satisfy the API 650 standards. In the case of constant stiffener, the minimum inertia value which is computed according to API 650 is used in all stiffener. In case of variable stiffener, the inertia of each stiffener is computed individually according to API 650. In this case, C, Unequal L angle with two different orientations and WT profile sections are investigated. In order to get meaningful comparison, the inertial values of different types of profiles are selected from catalogue in a way that they approximately equal to each other.

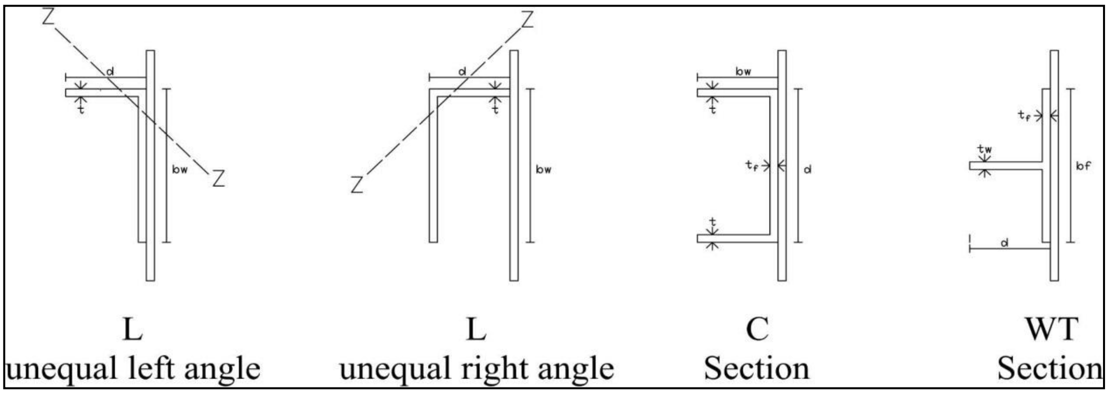

Figure 2 Type of stiffener profiles

The linear static, free vibration and buckling analyses are carried out using ANSYS commercial software for the designed tank according to API 650 standard. The tanks are modelled and analyzed using fine meshes. The FE model of the tank is shown in Figure 3. The stress distribution and deformations in the tanks and weight, fundamental frequency and critical buckling loads of tanks are observed. The effect of the number of course, stiffener, location of stiffener, type of stiffener is investigated.

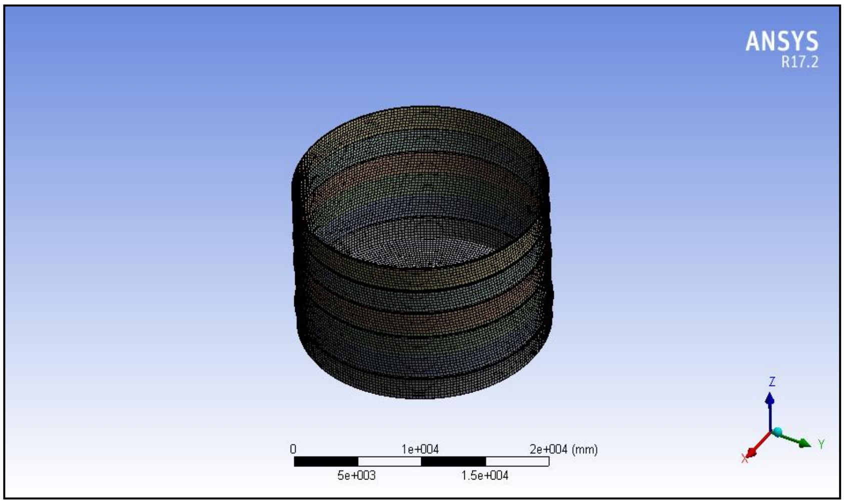

Figure 3 FE model of tank

RESULT AND DISCUSSION

The results of finite element analyses for static, free vibration and buckling is summarized in Table 3. The maximum equivalent stresses are very close to each other for all cases considered. The maximum equivalent stress is occurred at Case 5 with 6 courses and equal to 112.75 MPa which is less than minimum yield stress 250 MPa. The stress distribution for this tank is shown in Figure.4.

Table 3 The result of finite element analysis.

	Courses	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6
Max.von Mises Stress (MPa)	2	110.36	110.37	110.01	110.88	111.16	111.25
	3	110.36	110.38	110.38	110.31	111.19	110.3
	4	110.20	110.22	110.23	110.24	110.21	110.22
	5	111.73	111.74	111.75	111.74	111.74	111.71
	6	110.77	110.08	110.76	110.96	112.75	111.42
Max. Deformation (mm)	2	5.20	5.20	5.25	5.27	5.30	5.28
	3	5.22	5.22	5.22	5.22	5.28	5.22
	4	5.28	5.29	5.29	5.29	5.29	5.28
	5	5.32	5.32	5.32	5.32	5.31	5.32
	6	5.41	5.27	5.45	5.31	5.32	5.41
Fundamental Frequency (Hz)	2	6.4982	8.0534	8.1817	13.511	14.983	15.082
	3	6.7285	8.0357	8.3399	11.833	10.997	15.295
	4	6.9648	8.8812	8.8492	13.086	12.976	11.694
	5	7.2738	9.1952	9.1938	15.739	12.186	19.757
	6	7.6199	9.6296	9.5513	17.213	21.189	20.899
Buckling Multiplier	2	-1.1489	-1.2169	-1.2177	-1.2285	-1.2325	-1.2267
	3	-1.1244	-1.1738	-1.1748	-1.1793	-1.1813	-1.1813
	4	-1.0964	-1.2470	-1.2455	-1.2624	-1.2727	-1.2712
	5	-1.0772	-1.2434	-1.2443	-1.2823	-1.3107	-1.2832
	6	-1.0595	-1.1932	-1.1888	-1.2109	-1.2394	-1.2089
Weight	2	87386.00	88722.28	89024.05	89024.05	91959.11	88966.52
	3	83440.00	85154.74	85212.55	85212.55	87293.65	84643.26
	4	78499.00	81876.13	81593.72	81593.72	83589.10	83491.31
	5	74352.40	77037.52	77254.83	77254.83	84170.40	76992.84
	6	70600.70	73697.67	74101.41	74101.41	82191.12	73702.55

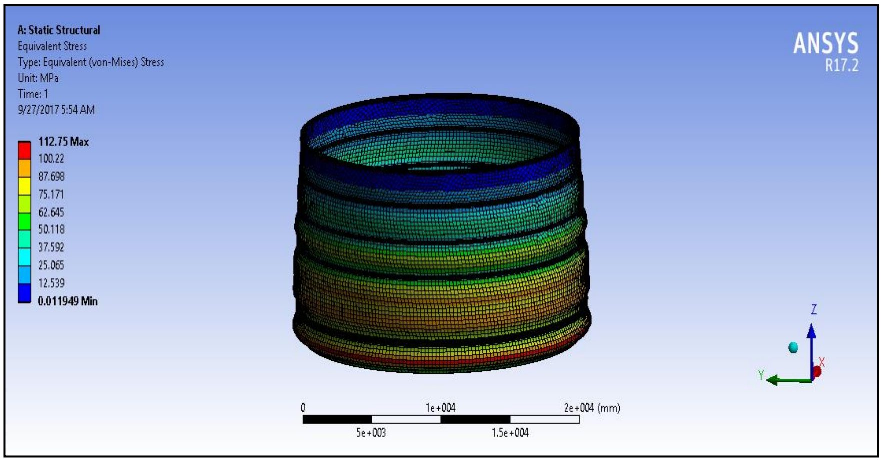

Figure 4 The maximum equivalent stresses

The maximum deformations are again very close to each other for all cases considered. The maximum deformation is occurred at Case 3 with 6 courses and equal to 5.45 mm. The deformation for this tank is shown in Figure 5.

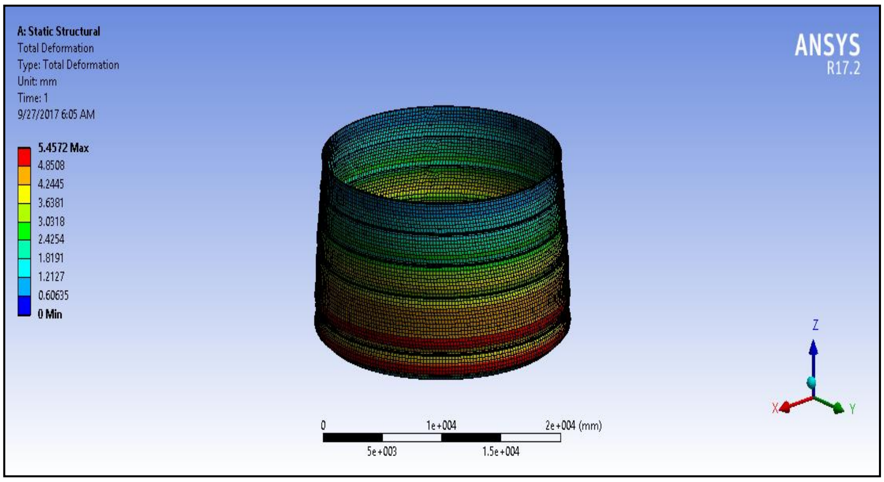

Figure 5 The maximum deformations

The one of the main reason of failure of tank is buckling. The buckling analyses of the tank are carried out and the buckling multiplier are computed and presented in Table 3. The worst case is the tank without stiffener. The best solution against buckling is obtained in Case 5 where C section stiffener is used. The maximum buckling multiplier is occurred at Case 5 with 5 courses and equal to -1.3107. The corresponding buckling mode shape is shown in Figure 6.

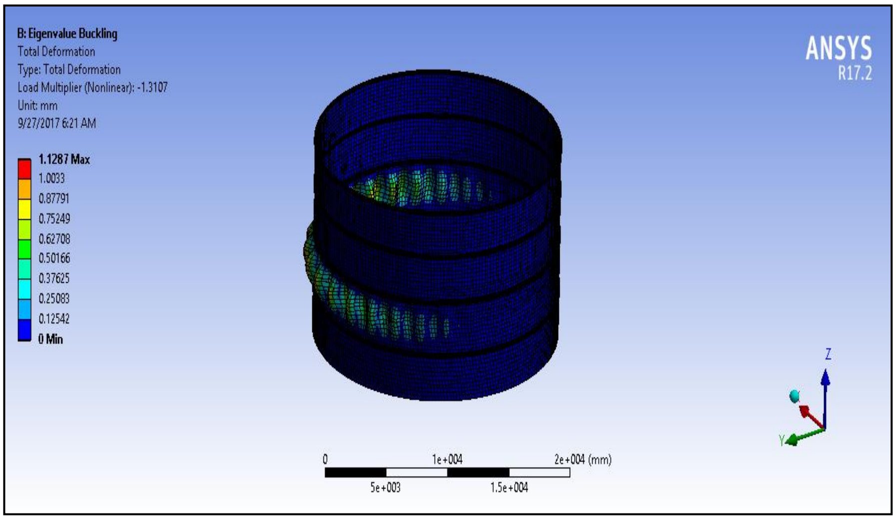

Figure 6 The maximum buckling multiplier

The seismic behavior of the tanks is investigated by studying fundamental frequency. The maximum fundamental frequency is occurred at Case 5 with 6 courses where C section stiffener is used and equal to 21.189mm. The corresponding mode shape is shown in Figure 8. The lowest fundamental frequencies are obtained in Case 1 as expected.

The weight of the tanks decrease with increasing number of courses. The lightest tank is obtained in case of without stiffener. The heaviest tanks are found in case of C section stiffeners.

CONCLUSIONS

In this paper the preliminary design of elements of a circular liquid tank by the API was performed. With obtained dimensions of elements, tank was modeled in the software package ANSYS, and values of maximum stresses and deformation were computed and compared. The stiffeners improve the static, buckling and dynamic behavior of the tank WT and C section stiffener show better performance. When the number of the courses increase the weight of the tank is reduced meanwhile the structural behavior of the tank does not change so much.

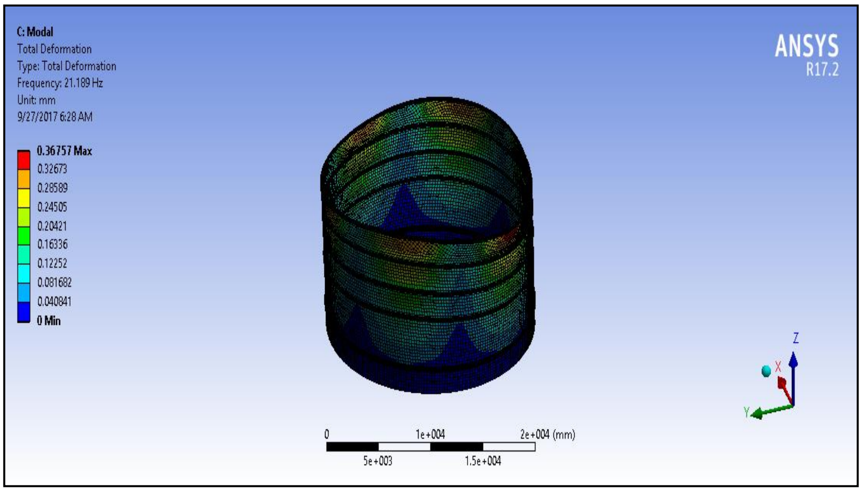

Figure 7 The maximum fundamental frequency

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